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EXCITATION OF DETONATION BY SHOCK WAVES (SELECTED PORTIONS)

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13. ABSTRACT

Current theoretical views on the mechanism of excitation of detonation are first discussed. Excitation by shock waves is then treated at length. The effects of various parameters, such as shock wave velocity, temp., pressure, duration of action, distance and dimensions of passive charge, etc., on initiation of detonation are considered, and appropriate formulas and relations are given. The impulse initiation of detonation of explosives is characterized by 3 phases; shock wave initiation of chem. reactions, growth of this reaction in the solid explosive, and appearance of the detonation wave. Factors favoring development of these phases are discussed. An exptl. study to check some ideas is then described. The study included detn. of the distance of transfer of detonation through air and steel depending on the diam. and type of passive charge (trotyl, stabilized hexogen GFG-2, GNDS, NTFA and V-5), and detn. of min. crit. parameters of the shock wave for initiating the detonation. Photoregistration was done by using the SFR-2 App. Tables curves, and photographs obtained are d'' ssed.
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Hexogen/(U)GFG2 Explosive						
(U)GNDS Explosive						
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EXCITATION OF DETONATION BY SHOCK WAVES (SELECTED PORTIONS)

CONTEMPORARY CONCEPTS ON A MECHANISM FOR THE EXCITATION OF DETONATION

ABBREVIATIONS

кр = critical
пог = flow
у.в. = shock wave
бок = lateral
оч = seat
з = charge
пр = limiting
осев = axial
н = initial
зад = delay

The excitation of the detonation of explosives can be realized under the direct action of an initiating impulse or by shock wave. For the excitation of the detonation of charges of heat-resistant explosives in shoot-through-explosive borehole equipment, both methods are used.

The blasting of the HE [high explosives] in detonators, as well as in charges with their direct contact with thin-walled

detonators is accomplished with the aid of the initiating impulse. In this case, "critical" for the excitation of detonation is the effect of the initiating shock wave and the detonation products possessing high pressure and high temperature. The question of the excitation of the detonation of charges by the direct initiating impulse is sufficiently studied and described in the literature. In the transmission of the detonation to the detonating cords or to charges of HE through a connection piece, the excitation of detonation is achieved by a shock wave.

Let us examine in more detail the question of the mechanism for the excitation of detonation under conditions of the initiation of charges of HE by shock waves.

In the excitation of the detonation form of explosion by the initiating impulse in the presence of an air barrier, detonation in a passive charge appears as a result of the direct igniting action of a shock wave and products of the explosion which were formed during the detonation of an active charge.

The experiments carried out by us showed that at the maximum distances of reliable detonation the speed of the shock wave at the moment of its approach to a passive charge of phlegmatized hexogen (compound of GFG-2) with density $\rho_0 = 1.65$ g/cm^3 is approximately equal to 3100 m/s, which corresponds to a pressure at the wave front of 100 at and to a temperature of approximately 3800°K. With the total reflection of the wave from the end of the charge the pressure increases to 900 at and the temperature exceeds 10,000°K.

It is evident that at so high a temperature the air wave will possess good initiating (igniting) capability even with the very small ($\tau \leq 10^{-6}$ s) duration of its action. Furthermore, in this case the shock wave which arose in the most passive charge (with its sufficient density), will not play any noticeable role in the mechanism for the excitation of its detonation.

When detonation is transferred to a passive charge through solid media (water, metals, glass, etc.), the only factor which causes its emergence is the shock wave which entered the passive charge from the transmitting medium - the so called initiating shock wave (ИУВ) [IUV] which is capable of exciting detonation in HE only with sufficiently high intensity. Only in this case, as a result of local heatings or shock compression of the HE a temperature can arise in the charge sufficient for the emergence of an intensive chemical reaction.

Many works [10, 19, 36, 40, 63, 87, 90, 92, 93, 95, 96, 97, 99, 102, etc.] are devoted to the investigation of the blast effects on HE and the law of the impact compressibility of many explosives has been established. I. Skey and D. Sibi [as transliterated] [102] showed that for HE with a sufficiently large charge density the linear dependence is well satisfied

$$D=a+bv, \qquad (27)$$

where D is the speed of the shock wave; v is the flow velocity behind its front; a and b are experimentally established coefficients which, over a wide range of pressures, remain constants (Table 23).

Table 23. The experimental values of coefficients a and b for some typical HE and inert materials.

Explosive	Density, g/cm^3	a, m/s	b
Trotyl (pressed)	1.60-1.62	2,390	2.05
Trotyl (liquid)	1.47	2,000	1.68
Hexogen	1.72	2,710	1.86
Composition "D"	1.62	2,400	1.66
Plexiglass	1.18	2,710	1.57
Copper	8.43	3,900	1.46

For a number of explosives the critical parameters ($p_{кр}$ and $D_{кр}$) of the initiating shock wave are determined with which it is still capable of exciting a stable detonation in the charge. These critical parameters increase substantially with an increase in the charge density. Thus, for trotyl, with a density change from 1.0 to 1.63 g/cm^3 the value of $p_{кр}$ changes (according to data of different authors) from $(8.0-9.0)\cdot 10^3$ to $(1.30-1.50)\cdot 10^5$ at. So abrupt a change in the value of $p_{кр}$ is explained by the fact that in proportion to an increase in the charge density the role of local heatings decreases to an even greater extent and the role of the impact heating of the HE in the mechanism for the excitation of detonation increases accordingly.

The first experiments for the determination of the critical parameters of the initiating shock wave with the diameters of the charges considerably in excess of the maximum were conducted in 1946 by B. I. Shekhter [15]. Later, such experiments were conducted in a number of other works [10, 19, 36, 40, 63, etc.].

V. S. Il'yukhin and P. F. Pokhil, during the investigation of the transmission of a detonation through solid media, determined the critical pressures of initiation for some explosives [40].

The work of A. F. Belyayev et al. [19] is devoted to an investigation of the critical pressure of initiation during transmission through the air.

A. N. Afanasenkov et al. [10] explained that with the transmission of the detonation through the air in the case of the use of cylindrical active charges, the excitation of detonation at a distance greater than 10 radii causes an air shock wave, and with the use of spherical active charges this distance is equal to 4.5 radii of the charge. With lesser distances, explosion products also participate in the process of the excitation of the detonation.

The values of $p_{кр}$ given in the literature for HE are sometimes contradictory. This is explained first of all by differences in the conditions of the experiment (different dimensions of the active and passive charges, etc.), and consequently, by the dissimilar duration of the effective action of the initiating shock wave on the initial focus of initiation in a passive charge.

K. Johnson et al. [96] convincingly showed that corresponding to each value of $p_{кр}$ at the front of the initiating shock wave is a certain minimum duration (τ_{min}) of its action (Table 24).

Table 24. The minimum duration of action of the initiating shock wave.

Explosive	Diameter of charge, mm	Critical parameters of the initiating shock wave	
		$p_{кр}$, at	τ_{min}, s
Tetryl - trotyl alloy	33.0	$9\cdot10^4$	$1.1\cdot10^{-6}$
Hexogen - trotyl alloy	33.0	$5\cdot10^4$	$0.6\cdot10^{-6}$

With the values of $p_{кр}$ given in Table 24, but with $\tau < \tau_{min}$ a stable detonation in a charge cannot be excited. However, with an increase in the intensity of the initiating shock wave the detonation of charge can also arise in the case of a briefer action.

In the experiments of M. Charles [99] the initiating shock wave arose in the charge as a result of its collision with a fast-moving bullet. The advantage of this method is that the time of action of this wave is controlled by the dimensions of the bullet and is determined by the total transit time of the compression wave along it and the path of the wave of rarefaction reflected from the end.

G. G. Rempel' [63] showed that the critical diameter of the initiating shock wave is changed noticeably to a certain limit with a change in the diameter of the initiated charge. The results

obtained by it have mainly a qualitative significance. A quantitative estimation causes doubt since the excitation of detonation was achieved not by a pure shock wave, but by direct contact with the initiator.

The facts noted above and some regularities which occur with the excitation of detonation by shock waves can be explained on the strength of the correct representations of the process of the impact initiation of HE charges. This process is characterized by three stages: 1) excitation of a chemical reaction in the charge under the action of the initiating shock wave; 2) the development of the process; 3) the emergence of the detonation wave.

Stage I. The amount of energy released during a reaction under the pressure of the initiating shock wave is an exponential function of the temperature which arises in the HE with its shock compression and it also depends on the time of its action. For the emergence of a detonation in a passive charge, it is necessary that this energy be at least sufficient for maintaining the constancy of the parameters of the initiating shock wave on the section of emergence.

Stage II. The transition of a shock wave into a detonation wave with the critical parameters of the former usually proceeds at some distance from the origin of the charge. Let us call this section the transition zone. The processes which proceed in this zone were studied by A. N. Dremin et al. [36, 92].

The investigations showed:

1. Under the critical conditions of initiation, the parameters of the shock wave on a considerable part of transition zone remain more or less constant.

2. The detonation of the charge arises at a velocity close to critical.

3. Detonation is excited at the end point of the transition zone not right after the approach of the shock wave to it, but with a certain delay connected with the geometry of the charge and the circumstance that it arises in the depth of the charge on the surface of a shock wave not relieved by lateral waves of rarefaction.

In certain cases, for example during the transmission of the detonation through the air, the transition zone is absent and detonation begins practically after some delay at the end of the charge. With transmission through solid media the length of transition zone (l) depends on the intensity of the initiating shock wave which is approaching the charge. Figure 21 shows the dependence of this length as well as the detonation velocity (D) and the flow velocity (r_{nor}) for pressed trotyl with a density of 1.59 g/cm^3 on the pressure of the initiating shock wave. The rapid chemical reaction excited in the charge in the process of the motion of this wave, in turn, is the source of the successive emergence of the elementary compression waves in it with aid of which the energy is pumped from the transfrontal zone to the shockwave front. These waves move along the medium excited by the shock wave at a rate of v + c, exceeding the initial velocity of the initiating shock wave. Every subsequent compressional wave moves along a denser medium, in consequence of which at a certain distance from the charge, as a result of their superposition, the velocity and amplitude of the shock wave begin to increase.

The expressed considerations about the mechanism of the accelerated chemical reaction are convincingly confirmed by the following experimental data:

1) under the limiting conditions of the excitation of detonation, the acceleration of the initiating shock wave, as a rule, does not begin immediately, but at a certain distance from the end of the charge [93];

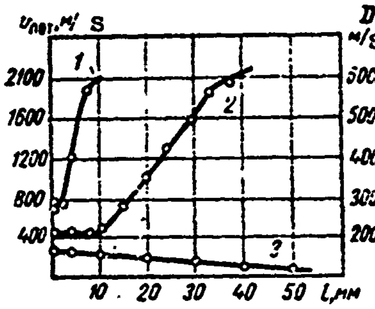

Fig. 21. The dependence of the detonation velocity and flow velocity on the pressure of the initiating shock wave (63): 1 - p = 35,000 at; 2 - p = 18,000 at; 3 - p = 12,000 at.

2) in a transition zone first the velocity of the shock wave falls even more or less noticeably although soon the detonation arises all the same;

3) observed in some experiments [90] was the constancy of the velocity of the shock wave in the charge on the section of its emergence, then - a sharp increase in its speed to a value which considerably exceeds the velocity of ideal detonation, and in the final stage - reduction to the velocity equal to the latter.

The propagation of the process on the initial section with an anomalously high detonation velocity frequently takes place when the velocity of detonation of the initiator considerably exceeds the detonation velocity of the initiated charge. However, in the case examined above the initial parameters of the initiating shock wave were considerably lower than the parameters of the normal detonation of the corresponding charges.

Stage III. Detonation arises at the end of a transition zone with a relatively low velocity and is initially a clearly expressed irregular process which, with a sufficient length of charge, changes over to a stationary form of detonation. Before passing on to a more detailed examination of the process of the emergence of detonation, it is advantageous to explain the basic qualitative differences between the phenomena which proceed in the transition zone and at a given final stage of development of the process.

In the opinion of A. N. Dremin et al. [36] the chemical reaction which arose under the effect of the shock wave should be considered from the very beginning as a detonation under imperfect conditions. As will be shown below, there can be no agreeing with this point of view.

It has been established that under critical conditions of initiation, simultaneously with the detonation wave in a passive charge a detonation wave which is propagated in the opposite direction and which fully completes the chemical reaction in the transition zone usually arises. When the detonation wave is not formed, the spread of the undecomposed matter on the initial section of the charge occurs.

The transition of a shock wave into a detonation at the final "point" of the transition zone is connected first of all with the fact that the parameters of the former in this case turn out to be sufficient for excitation, in a charge of a spontaneously developing chemical reaction leading, according to the conditions of a thermal explosion, to the spontaneous combustion of the HE and its violent "combustion" in the primary seat of initiation. This process, naturally, is accompanied by a more or less intense luminescence of the reaction products, which, in particular, also makes it possible to record the places of origin of the detonation and the speed of its propagation along the charge with the use of optical methods.

Thus, the maximum measure of the intensity of the chemical reaction in the initial seat of initiation and the minimum intensity of the initiating shock wave necessary for the excitation of detonation in it should be unambiguously determined by the critical parameters of the thermal explosion; the condition should be satisfied:

$$T_{\text{т. з}}=T_{\text{кр}};\quad \tau_{\text{т. з}}=\tau_{\text{кр}}, \tag{28}$$

where $T_{кр}$ is the critical temperature of spontaneous combustion of the seat of initiation; $\tau_{кр}$ is the delay time corresponding to it.

Hence, it is obvious that with a decrease in the time of the effect of the initiating shock wave on the HE, $T_{кр}$ of the shock wave increases, i.e., a more powerful shock wave is necessary for the excitation of detonation.

The duration of the effective action of the initiating shock wave is determined by the dimensions of the generator of the shock wave (length of the active charge, the diameter of the bullet, the dimension of the fragment element, etc.) and it depends substantially on the conditions for the penetration of the lateral waves of rarefaction and axial waves of relief into the initial seat of initiation.

The maximum time of the influence of the shock wave on the initial seat of initiation even with any large dimensions of active and passive charges cannot exceed the travel time of the lateral waves ($\tau_{бок}$) determined by the relation $d_{оч}/2c$, where $d_{оч}$ is the diameter of the seat of initiation and c - the speed of sound in a charge compressed by the initiating shock wave. Since in all our experiments the initial diameter of the seat of initiation was equal to the diameter of the charge, subsequently, by $d_{оч}$ we will mean $d_з$. Obviously if as a result of the small value of the diameter of the charge $\tau_{бок} < \tau_{кр}$, i.e., the travel time of the lateral wave of rarefaction is less than minimum time necessary for the realization of thermal explosion in the primary seat of initiation, then with the given power of the initiating shock wave the ignition of the HE and detonation will not arise.

From this it follows directly that with an increase in the diameter of the charge to a certain limit ($d_з = d_*$) the values of the critical parameters ($T_{у.в}$, $D_{у.в}$, $p_{у.в}$) of the initiating shock wave should decrease, which agrees with G. G. Rempel's data [63]

and is in full conformity with the results of the experiments given below.

The value of d_* can be approximately determined on the strength of the following premises:

1) under conditions of the excitation of the detonation of the shock wave, the initial seat of initiation is that region within the charge into which the lateral wave of rarefaction does not manage to penetrate during the time of action of the shock wave;

2) the smallest possible detonation velocity cannot be less than the so-called "critical detonation velocity", approximately equal to the detonation velocity of a damped explosion approaching the speed of sound in the charge;

3) the detonation can be excited in a passive charge with minimum velocity, and consequently with the minimum parameters of the initiating shock wave, only when the dimensions of the initial seat of initiation are not less than the so-called limiting diameter $d_{\text{пр}}$ of the charge.

The critical parameters of the initiating shock wave should increase in proportion to a decrease in the size of the initial seat of initiation. The width of the seat of initiation (L_p) behind the detonation front in this case is approximately equal to the limiting diameter ($L_p = d_{\text{пр}}$), and the time of the course of the reaction - to the relation $d_{\text{пр}}/D$.

The minimum diameter of the charge with which the rarefaction wave still will not have time to penetrate into the primary seat of initiation with a width equal to $d_{\text{пр}}$ will be determined by the condition:

$$t_{\text{бок}} \approx \tau_p, \qquad (29)$$

where

$$t_{бок} = \frac{d_з - d_{кр}}{2c}.$$

From formula (29) it follows

$$d_* \approx d_{кр}\left(\frac{2c}{D} + 1\right), \qquad (30)$$

where D is the velocity of the initiating shock wave; c is the speed of sound in the HE compressed by the shock wave.

Since $c/D \approx 1$, it is possible to accept:

$$d_* \approx 3d_{кр}. \qquad (31)$$

In the theory of thermal explosion [55, 67, 72, 83], as is known, the quantitative connection between values $T_{кр}$, $\tau_{кр}$, $d_з$ and the kinetic characteristics of the HE is established. In the determination of the limiting conditions of the emergence of the detonation in the primary seat of initiation it is necessary to accept $d_з = d_{пр}$ and $\tau_{кр} = [\tau_{бок}]_{кр}$, and knowing these values, on the strength of the dependences for a thermal explosion it is possible to calculate value $T_{кр}$.

Comparing the latter with the temperature of adiabatic heating of the HE by the initiating shock wave, it is possible to judge soundly the condition of the emergence and course of the chemical reaction in the primary seat of initiation. If the critical temperature is substantially higher than the temperature of adiabatic heating, then the basic role in the mechanism for the emergence of the reaction will be played by local heatings. The nearness of these values can serve as a reliable indication that the adiabatic heating of the HE plays the determining role.

If $d_з \geq d_*$, and the conditions for initiation remain unchanged, the only limiting factor affecting the duration of the effective action of the shock wave on the HE can be only the

longitudinal relief wave. If the total time ($t_{осев}$) necessary for the travel of the shock wave from the primary seat of initiation to the end of the passive charge and the relief wave of that distance $L_{оч}$ in the opposite direction is less than the value $t_{кр}$ then detonation does not arise. The limiting value of $L_{оч}$, beginning with which the axial relief wave will not succeed in penetrating into the primary seat of initiation during the influence of the initiating shock wave on it, is determined from the condition:

$$t_{осев} \approx t_{кр}. \tag{32}$$

THE RESULTS OF EXPERIMENTAL RESEARCH

To check the fundamental propositions expressed above experiments on the determination of the distances of transmission of the detonation through air and steel barriers depending on the diameter, casing, and length of the passive charge were conducted. The limiting values of the minimum critical parameters of the initiating shock wave with which detonation in the charge is assured and the delay times corresponding to them were also determined.

The Determination of the Limiting Diameter of Initiation

In all experiments, used as active charges were the cylindrical charges of regular phlegmatized hexogen with a density of 1.60 g/cm^3; the diameter of the charge 25 mm, length - 40 mm. Used as passive charges were charges of trotyl, GNDS and phlegmatized hexogen mark GFG-2 (Fig. 22, 23, Table 25).

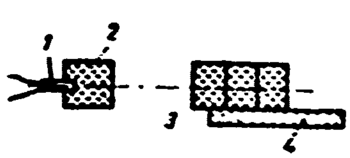

Fig. 22. Diagram of an experiment in the transmission of a detonation through the air. 1 - Electrical detonator No. 8; 2 - Active charge; 3 - Passive charge; 4 - Lead plate-control sample.

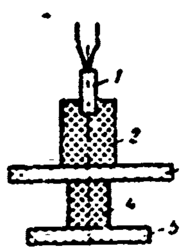

Fig. 23. Diagram of an experiment in the transmission of a detonation through a steel plate. 1 - Electrical detonator No. 8; 2 - Active charge; 3 - Steel connection piece; 4 - Passive charge; 5 - Lead plate-control sample.

As can be seen from Table 26 and Fig. 24 and 25, the maximum transmission distance of the detonation for three explosives, regardless of the nature of the transmitting medium (air, steel), is attained with approximately identical values of $d_{\text{э}}/d_{\text{пр}}$ which equal approximately 3, which is in full conformity with dependence (32).

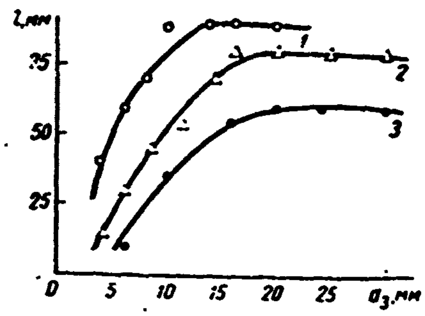

Fig. 24. The effect of the diameter of the passive charge on the distance of transmission of a detonation through the air. 1 - GNDS; 2 - GFG-2; 3 - TNT.

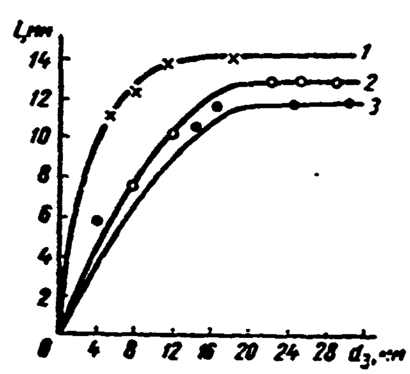

Fig. 25. The effect of the diameter of a passive charge on the distance of transmission of a detonation through a steel barrier. 1 - GNDS; 2 - TNT; 3 - GFG-2.

This result also testifies to the fact that the mechanism for the excitation of a detonation in a charge during its transmission both through dense media and through air is connected with the very same physical processes in spite of some important specific features which occur in the initiation of an explosion by air shock waves.

The determining role of the lateral waves of rarefaction in the relationship of the dependence of the critical parameters of the initiating shock wave on the diameter of the passive charge is also confirmed by the results of experiments on the transmission of a detonation to charges enclosed in a casing.

Table 25. Characteristics of passive charges.

The explosive of the passive charge	Density, g/cm^3	Critical diameter, mm	Limiting diameter, mm
Trotyl	1.58	3.0	8.0
GNDS	1.66	1.8	3.0
GFG-2	1.65	2.0-2.5	5.0-5.2

Table 26. The dependence of the distance of reliable detonation on the diameter of the passive charge.

The explosive of the passive charge	The relative value of the diameter of the charge		The distance (l) of transmission of detonation, mm	
	$d_з/d_{кр}$	$d_з/d_{пр}$	Through the air	Through a steel barrier
Trotyl	2	0.75	10	7
	3.3	1.25	35	10
	5.3	2.0	55	11
	8.0	3.0	60	12
	10.0	3.75	60	12
GFG-2	1.6	0.8	15	6
	3.2	1.5	45	8
	4.8	2.3	60	10
	6.4	3.1	80	11
	8.0	3.8	80	11
	9.6	4.6	80	11
GNDS	2.2	1.3	30	10
	3.3	2.0	60	11
	4.4	2.6	70	12
	5.5	3.3	90	14
	6.7	4.0	90	14

The charges were of phlegmatized hexogen GFG-2 with a density of 1.65 g/cm^3, the transmitting medium - air.

The results of experiments showed that with $d_з > d_*$ the presence of a casing, as one would expect, does not affect the distance of transmission of detonation.

With the inclusion of a passive charge in a sufficiently strong casing the maximum possible distance of transmission of detonation under these conditions can be achieved (as a result of the suppression of the lateral waves of rarefaction) with any practically sufficiently small diameter of charge.

To check the previously expressed considerations about the limiting conditions under which the axial rarefaction waves begin to have an effect on the distance of transmission of the detonation, special experiments were conducted (Table 27) with passive charges of GFG-2 with $d_з > d_*$ (diameter of charge was equal to 20 mm) on the determination of the distance of transmission of the detonation depending on the length of the passive charge.

Table 27. The effect of the length of passive charge on the distance of transmission of detonation.

Length of passive charge, mm	Transmission distance of detonation, mm	
	Through the air	Through steel
20	80	11
10	80	11
6	80	11
4	60	9
2	50	--

From the results of these experiments it can be seen that regardless of the transmitting medium (air, steel) a reduction in the distance of transmission of a detonation begins only with the length of passive charge equal to approximately 4 mm, which

corresponds, in the case of th^ emergence of a detonation at the end of the passive charge, to the value $d_*/4$ and follows from relationship (32).

The Photorecording of the Processes in the Excitation of the Detonation of Explosives

For determining the conditions of the emergence of a detonation in a passive charge and the parameters of the initiating shock wave experiments were accomplished in the photorecording of processes with specific distances of the reliable transmission of detonation with the use of a high-speed photorecorder SFR-2.

In all cases, used as an active charge was regular phlegmatized hexogen with a diameter of 25 mm, a height of 40 mm, and density of 1.65 g/cm^3, i.e., the same as in experiments for the determination of the dependence of the distance of detonation transmission on the diameter of the passive charge and other factors.

The velocity of the shock wave at various distances from the end of the active charge during the transmission through the air:

Distance, mm	Velocity of shock wave, m/s
15	4300
30	3940
45	3700
60	3320
80	3100
90	2950

In the transmission of a detonation through the air a charge of phlegmatized hexogen GFG-2 with a diameter of 20 mm and a density of 1.65 g/cm^2 was taken as the passive charge.

As a result of these experiments, it turned out that the velocity of an air shock wave at the moment of approach to the passive charge ($D_{y.s}$) comprised approximately 3100 m/s and the

initial detonation velocity in the passive charge (D_H) - 2900 m/s. Detonation begins at the very beginning of the charge, and the delay time up to the moment of the emergence of the detonation is equal to $(1.67-1.7) \cdot 10^{-6}$ s. Transition to the normal detonation velocity ($D_{max} \approx$ 7800 m/s) occurred, as a rule, at a distance of more than 20 mm from the end of the charge.

A typical photogram of the process of transmission of a detonation through the air is shown on Fig. 26 (at the end of the passive charge a screen of cardboard was placed along its circumference).

Fig. 26. Photogram of the process of transmission of a detonation through the air AB - shock wave; BC - the detonation of a passive charge.

In the transmission of a detonation through a steel barrier charges of trotyl, GNDS substance and phlegmatized hexogen GFG-2 were used as the passive charges.

The distance (l) to the start of the detonation of a passive charge, the initial detonation velocity (D_H) of the passive charge and time (t_1) from the moment of the emergence of the detonation wave of the active charge to the moment of the arising of the detonation in the passive charge can be determined directly from the photogram (Fig. 27).

Fig. 27. Photogram of the process of the transmission of a detonation through a steel barrier. AB - detonation of an active charge; CE - detonation wave; CD - detonation of a passive charge.

Delay time of detonation ($\tau_{зад}$) in the place of its emergence can be calculated if we know the transit time (t') of the shock wave through a steel barrier and the transit time (t'') of the initiating shock wave over the transition zone of the passive charge

$$\tau_{зад} = t_1 - t_2. \qquad (33)$$

where $t_2 = t' + t''$.

For determining the value of t' special experiments were conducted in the photorecording of the processes according to the diagram scheme on Fig. 28.

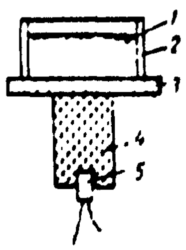

Fig. 28. Diagram of an experiment on determining the delay time of detonation. 1 - Water; 2 - Glass container; 3 - Steel barrier; 4 - Active charge; 5 - Electrical detonator.

The moment of the emergence of the shock wave on the external surface of the metal corresponds to the moment of the formation of a shock wave in water which is clearly fixed on the photograph.

The time of the passage of the initiating shock wave (t'') through a transition zone of sufficient length is determined with the use of the method developed by B. I. Shekhter and L. A. Shushko. Fine holes are drilled at the end of the passive charge and on a section of the transition zone at a certain distance from one another. The blasting of the charge is accomplished with its simultaneous brightening. With the movement of the initiating shock wave along the transition zone, the beams of light which are formed during the glow of the exploded wire or other light source and pass through the holes in the passive charge will be darkened.

With the use of the photogram (Fig. 29) the velocity ($D_{y.B}$) of the shock wave in the passive charge is determined and the time of the passage of the initiating shock wave through the transition zone of the charge is calculated:

$$t'' = \frac{l}{D_{y.B}}. \quad (34)$$

Furthermore, according to this method it is possible also to directly determine the time (t') of the passage of the shock wave through a steel barrier.

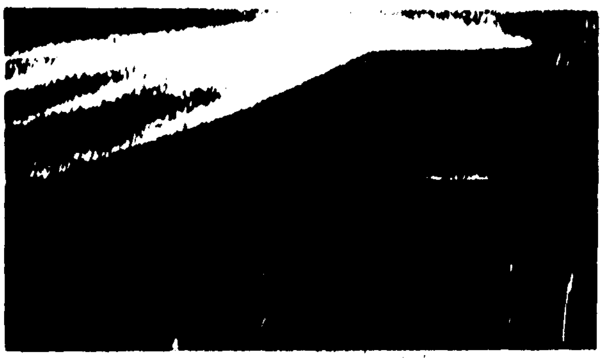

Fig. 29. Photogram of the passage of a shock wave in a passive charge. AB - detonation of the active charge; CDE - the initiating shock wave in a passive charge; EK - detonation of the passive charge.

If distance to the origin of detonation is small and it is not possible to make a hole in a section of the transition zone, the initial velocity of the initiating shock wave in the passive charge should be determined using the data on the compressibility of steel and the charge of HE as well as the speed of transit of the shock wave over the steel barrier which, under conditions of our experiments, is equal to 5150-5200 m/s (Table 28).

Table 28 shows that with $d_з = d_*$ the distance to the origin of detonation for charges with a given density equals: for compound GFG-2 - 1.7 mm, for the substance GNDS - 4.6 mm, for trotyl - 6.2 mm.

Table 28. The velocity of the initiating shock wave and delay time of detonation in passive charges.

Explosive	Characteristic of the passive charge		Speed of the initiating shock wave, m/s	Length of transition zone, mm	Initial detonation velocity, m/s	Delay time, m/s	
	ρ_{HE} g/cm^3	$d_з = d_*$ mm				Experimental	Calculated
Trotyl	1.58	24.5	3220	6.2	3050	2.30	2.23
GFG-2	1.65	16	3360	1.7	3200	1.30	1.40
GNDS	1.66	10	2900	4.6	3120	0.95	1.04

The normal detonation velocity during transmission through a steel barrier, unlike transmission through the air, is attained at a distance of 2-3 mm from the origin of the detonation.

The critical velocity of the initiating shock wave with GFG-2 was somewhat higher than with trotyl, which agrees with B. I. Shekhter's data [15] and, apparently, is a characteristic of the phlegmatized hexogen.

In accordance with the previously expressed propositions delay time ($\tau_{зад}$) of the detonation should be equal to the period of the delay of a thermal explosion of the primary seat of

initiation, i.e., to the value $\tau_{кр}$ which, with the limiting conditions of the excitation of the detonation, in turn, is equal to the time of the effective action of the shock wave:

$$\tau_{у.в} \approx \frac{d_{кр}}{2c_{у.в}}.$$

Calculations show that with the values of the critical velocities of the initiating shock wave obtained by us

$$c_{у.в} \approx 1{,}15D_{у.в}.$$

Table 28 also shows that the calculated values $\tau_{у.в}$ and the values established from the experiment $\tau_{зад}$ are of one order (maximum deviation does not exceed 10%), which can serve as the confirmation of our impressions of the processes of initiation by shock waves.

With a velocity increase in the initiating shock wave, which is attained by a decrease in the thickness of the steel barrier, the section of the transition zone (distance to the origin of the detonation of the passive charge) is reduced and the delay time of the emergence of the detonation noticeably decreases.

With $d_з < d_*$ the critical speed of the initiating shock wave increases noticeably and the delay time, as one would expect, decreases accordingly (Table 29).

The experiments also show that with $d_з < d_*$ the critical velocity of the initating shock wave remains constant and no regular change in the values l and $\tau_{зад}$ is observed.

For investigating the conditions of the excitation of the detonation of charges of heat-resistant HE, experiments were conducted on determining the distance of transmission of detonation and the photorecording of the process with limiting distances of

reliable detonation of charges of heat-resistant HE pressed into a duralumin sleeve with an inside diameter of 10 mm.

Used as an active charge was the heat-resistant electrical detonator mark TED-2. Charges of GNDS, NTFA and V-5 were investigated.

Table 29. The effect of the diameter of the passive charge and the distance of transmission of the detonation on the velocity of the initiating shock wave.

Explosive	Thickness of the steel barrier, mm	Diameter of the charge mm	Speed of the initiating shock wave, m/s	Distance to the origin of the detonation of the charge, mm	Delay time of detonation, μs
GNDS	14	10	2900	4.6	0.95
	11	10	3360	3.2	0.30
	7.7	10	3900	1.6	0.15
	11	6	3360	3.7	0.35
GFG-2	11	16	3360	1.7	1.30
	8	10	3860	1.8	0.45

In the determination of the transmission of a detonation (Fig. 30), it was clarified, that the distance of reliable transmission of a detonation through a steel barrier to a charge of GNDS and NTFA is equal to 1.5 mm, and to charges of V-5 - 1 mm (Table 30).

Fig. 30. Photogram of the passage of an initiating shock wave along a charge of heat-resistant HE. AB - the initiating shock wave in a passive charge; BC - detonation of the passive charge.

Table 30. Values of the initial velocity of the initiating shock wave, distance to the origin of detonation of the charges, and the calculated delay time of the detonation.

Explosive	Density, g/cm^3	Thickness of plate, mm	Velocity of the initiating shock wave in the passive charge, m/s	Distance to the origin of the detonation, mm	Delay time of detonation, m/s
GNDS	1.66	1.5	3000	3.5	0.50
NTFA	1.62	1.5	3400	2.3	1.30
V-5	1.62	1.0	3700	4.6	1.55

The velocity of the initiating shock wave necessary for the excitation of the detonation of substances NTFA and V-5 is higher than for GNDS; it is highest in the product V-5 which possesses low susceptibility to a detonation impulse.

The results of the analysis and generalization of published data and of the theoretical and experimental research carried out on the mechanism for the initiation of the detonation of HE by shock waves make it possible to draw some conclusions.

1. With the limiting conditions of excitation of detonation, the acceleration of the chemical processes in the transition zone of a passive charge is connected with the emergence of elementary waves of compression in it with aid of which the "transfer by pumping" of the energy of the chemical reaction from the transfrontal zone to the shockwave front occurs.

2. The transition of the shock wave at the end of the transition zone to the detonation zone is connected with excitation under the influence of the initiating shock wave in the primary seat of initiation of a spontaneously developing chemical reaction which leads, in accordance with the laws governing a thermal explosion, to the spontaneous combustion of the HE in this seat.

In this case, the critical parameters of the initiating shock wave can be unambiguously determined from the conditions

$$T_{i.s}=T_{\kappa p};\quad \tau_{i.s}=\tau_{\kappa p},$$

where $T_{\kappa p}$ is the critical temperature of spontaneous combustion; $\tau_{\kappa p}$ is the delay time corresponding to this temperature.

3. Detonation can be excited in a passive charge with minimum velocity and, consequently, with the minimum parameters of the initiating shock wave only when the diameter of the initial seat of initiation is no less than the limiting diameter of the charge.

On the strength of this premise and with consideration of the effect of the lateral waves of rarefaction on the duration of the effective influence of the shock wave on the HE, the relationship is obtained which determines the minimum value of the diameter of the charge ($d_* = 3d_{np}$), with a further increase in which a reduction in the critical parameters of the shock wave no longer takes place.